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ASSESSMENT OF SOIL LOSS SUSCEPTIBILITY IN SANTA RITA WATERSHED IN SOUTHERN BRAZIL

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KEYWORDS

RUSLE, soil loss index, soil loss tolerance, water erosion

ABSTRACT

Estimation of soil loss susceptibility is of great importance for the management of watersheds. Thus, several models for soil loss prediction have been proposed. This study estimated the total annual soil loss for the Santa Rita watershed, located in southern Brazil, using the Revised Universal Soil Loss Equation. In addition, a classification to soil loss index (I_{SL}) was proposed to identify regions with critical soil loss values. Altitude, slope, land use, and soil class data were applied to the model, in addition to spatial information for 78 soil samples collected within the study area. It was found that there is an average annual loss of 35.94 Mg ha^{-1} year^{-1}, with the most substantial loss occurring in areas with predominantly exposed soil and annual cropping. Furthermore, the I_{SL} values indicated that approximately 50% of the study area is experiencing erosion estimates above the tolerable limit. Results emphasize the need for changes in conservation and application practices present in the watershed, considering land use and soil bearing capacity.

INTRODUCTION

The water and sediment delivery through water bodies towards the oceans is a natural consequence of the water cycle. With population growth and intensification of anthropogenic activities associated with changes and intensive use of soil, the water erosion process is accelerated and intensified (Napoli et al., 2016), promoting soil loss to occur above the tolerable limits established in the literature. An increase in soil loss is directly associated with the number of available nutrients, reducing agricultural productivity and causing eutrophication of water bodies (Bakker et al., 2007). Studies have reported that soil disaggregation interferes with basic soil properties relevant to the cultivation system, in addition to increasing production costs (Derpsch et al., 2014; Reicosky, 2015).

In tropical and subtropical regions, agricultural practices have intensified soil erosion, mainly because of the difficulty of implementing appropriate soil conservation measures (Beskow et al., 2009). Some research indicates that the use of conservationist measures depends on several factors, such as economic viability, lack of knowledge about new techniques, and social or cultural aspects (Wreford et al., 2017; Rocha et al., 2020). In this context, it is necessary to map soil loss susceptibility for the planning and management of watersheds (Markose & Jayappa, 2016). However, there is still a shortage of data obtained in the field, which is time-consuming and costly (Batista et al., 2017). Several mathematical models for estimating water erosion and sediment yield have been proposed, including the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), Water Erosion Prediction Project (WEPP) (Flanagan & Nearing, 1995), Erosion Productivity Impact Calculator (EPIC) (Sharpley & Williams, 1990), Universal Soil Loss Equation (USLE) (Wishmeier & Smith, 1978), and Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997).

RUSLE is an erosion model designed to predict the long-term average annual soil loss (A) (Renard et al., 1997), which has been widely used, especially in places with limited or non-existent data (Steinmetz et al., 2018). Estimates were made based on climatic variables (factor R), soil (factor K), topographic (factors L and S), and soil use, management, and conservation conditions (factors C and P, respectively). According to Merritt et al. (2003), RUSLE was developed for small hillslopes; however, several studies have used it to estimate soil erosion at the watershed scale (Gianinetto et al., 2019; Gomes et al.,

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2019; Panditharathne et al., 2019; Lense et al., 2020). With the advent of Geographic Information Systems (GIS), it is possible to estimate soil loss pixel-by-pixel. However, this model does not provide sediment deposition and sediment delivery (Benavidez et al., 2018). Regarding watershed management, estimating soil erosion rates in subwatersheds with different characteristics is essential for soil and water conservation projects (Kavian et al., 2017).

The spatial variability of soil loss susceptibility at the watershed scale has helped several studies concerning the public water supply. In this context, some authors have studied other negative effects of water erosion, such as siltation of channels and reservoirs and compromised water quality (Valadão et al., 2018; Santos et al., 2020). The Santa Rita Watershed (SRW) is a subwatershed of the Fragata River Watershed (FRW), which is of great socioeconomic importance in the region and is responsible for part of the water supply in the city of Pelotas, RS (Valadão et al., 2018). Furthermore, SRW has a large agricultural area within its natural space, affecting water quality and modifying the landscape that encompasses its water resources. Therefore, the present study aimed to obtain the RUSLE parameters, total annual loss, and proposed a classification for the index soil loss, allowing the identification of the most susceptible soil loss places in the Santa Rita watershed, located in the Rio Grande do Sul Southern Brazil.

MATERIAL AND METHODS

Study area and database

The study area comprises the Santa Rita watershed (SRW), 9.10 km², located in the city of Pelotas, south of Rio Grande do Sul (RS) (Figure 1). The SRW is a subwatershed of the FRW, which is strategic for economic and social development in the state of RS (Beskow et al., 2016). The region's climate is Cfa Köppen’s type, humid subtropical, characterized by hot summers with temperatures above 22 °C and an annual average rainfall of 1,385.6 mm (Alvares et al., 2013).

SRW is a direct affluent of the Moreira Water Treatment Plant (Moreira WTP) (Figure 1). It consists of an untreated water accumulation dam and serves only to provide the treatment plant, passing the water through filters and completing conventional treatment. In addition, Moreira WTP supplies reservoirs responsible for delivering water to several neighborhoods in the city of Pelotas.

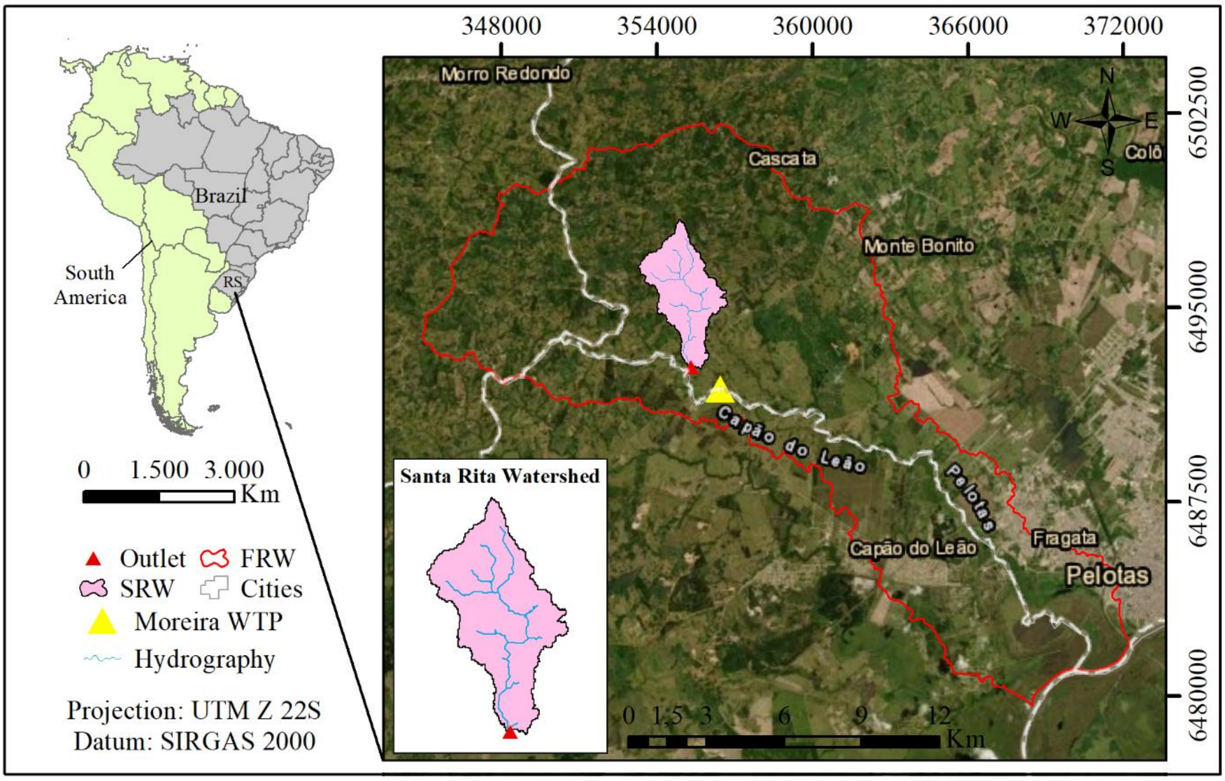

FIGURE 1. Location of the Fragata River Watershed (FRW) and the Santa Rita Watershed (SRW) in the state of Rio Grande do Sul (RS), Southern Brazil.

Fully inserted in the Pampa biome, the SRW is characteristic of the region, predominantly rupestrian vegetation, with areas destined for agriculture and grassland in the great majority (Lupatini et al., 2013). The soil classes of the SRW were obtained from mapping performed by Cunha et al. (2006). The soils present in the SRW are Red-Yellow Argisol (72.31%), Yellow Argisol (25.52%), and Haplic Planossol (2.17%) (Figure 2a). In addition, data from the granulometric analyses performed on 78 soil samples distributed throughout the SRW (Table 1) was used.

Land use classes were obtained through supervised classification carried out in the software QGIS 3.4.3, using false-color composite 6-5-4. In addition, field-level investigations were conducted before classifications to observe the different uses and management in the watershed. A Landsat 8 image with a spatial resolution of 30 m taken on March 8, 2019 with point orbit 221082, made available by the United States Geological Survey (USGS), was used. As a result, the following classes of land use were identified: water bodies (0.77%), annual cropping (14.11%), grassland (52.27%), exposed soil (4.76%), and native forest (29.09%) (Figure 2b). In addition, a quarry area (~ 0.4 km²) was identified but disregarded in the analysis following the suggestions of Martín Duque et al. (2015).

Delimitation and characterization of the SRW were performed automatically using ArcGIS 10.1. software (ESRI, 2014). The digital elevation model (DEM) of the Shuttle Radar Topographic Mission (SRTM), made available by the USGS, was used. All products derived from the DEM were used with a spatial resolution of 30 m.

SRW altitudes ranged from 42 to 228 m, with an average altitude of 108 m (Figure 2c). Based on the slope classification proposed by EMBRAPA (1979), it is clear that the watershed has a predominantly undulated topography, with 38.98% and 47.42% of the area framed as smooth-undulated (3% – 8%) and undulated (8% – 20%), respectively. The flat regions (0% – 3%) of the watershed corresponded to 11.42%, whereas 2.18% of the area had a strongly undulated topography (20% – 45%) (Figure 2d).

TABLE 1. Minimum, average, and maximum values for the clay, silt, and sand fractions obtained in each soil class of the Santa Rita Watershed (SRW) located in Southern Brazil.

Soil classes	-	% Clay	% Silt	% Sand	
				Total	Very thin
Yellow Argisol (Acrisol[1])	Minimum	16.2	19.2	41.9	4.8
	Maximum	32.6	30.4	54.5	6.2
	Average	24.4	24.8	48.2	5.5
Red-Yellow Argisol (Acrisol[1])	Minimum	16.6	13.2	27.9	3.1
	Maximum	39.6	46.1	60.0	6.7
	Average	28.1	29.6	43.9	4.9
Haplic Planosol (Planosol[1])	Minimum	16.2	18.1	52.9	5.9
	Maximum	19.2	24.7	57.7	6.4
	Average	17.7	21.4	55.3	6.1

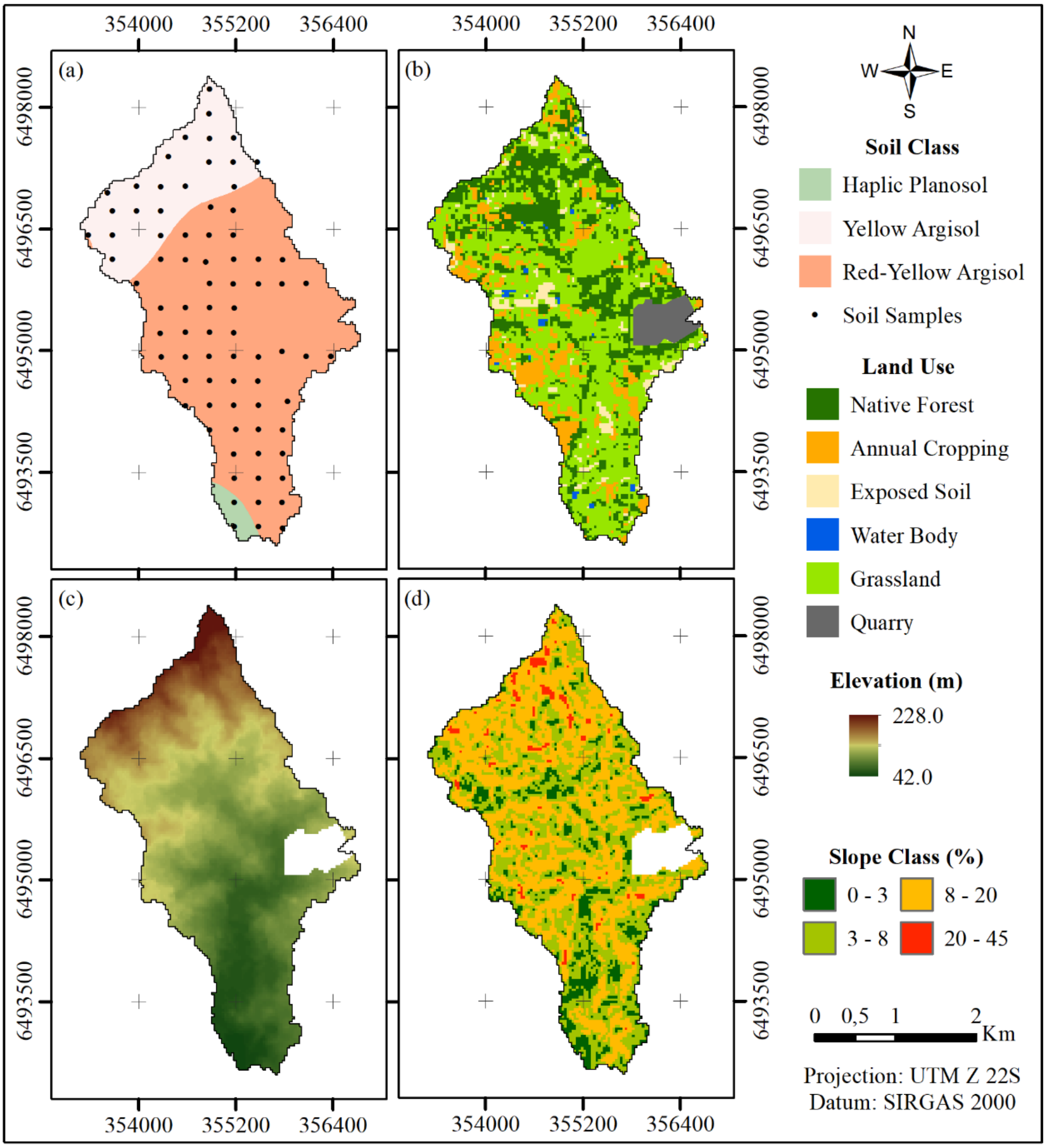

FIGURE 2. (a) Soil samples and soil classes, adapted from Cunha et al. (2006); (b) Land use maps; (c) digital elevation model; and (d) slope classes of the Santa Rita Watershed (SRW) located in Southern Brazil.

The Revised Universal Soil Loss Equation

The Revised Universal Soil Loss Equation (RUSLE) described by Renard et al. (1997) (Equation 1) was used to estimate soil loss. The RUSLE equation was performed with ArcGIS 10.1® software (ESRI, 2014), using the pixel as the unit of analysis, conserving the spatial resolution of the database (30 m).

$$A = R\ K\ LS\ CP \qquad (1)$$

Where:

A is the average annual soil loss per unit area (Mg ha^{-1} $year^{-1}$);

R is rainfall erosivity (MJ mm ha^{-1} h^{-1} $year^{-1}$);

K is soil erodibility (Mg h MJ^{-1} mm^{-1});

LS is the topographic factor (dimensionless), and

CP is the soil use, management, and conservation conditions (dimensionless).

Rainfall erosivity (R)

Due to the lack of data throughout the national territory, Mello et al. (2013) proposed R factor equations for Brazilian regions. These equations were obtained from multiple regressions with simplified and easily acquired parameters, such as altitude, latitude, and longitude. This study opted for using the equation proposed for the southern region of Brazil (Equation 2) to obtain the values of R.

$$R = 2610770 - 60.44Z + 98.839LO - 1114.68LA^2 + 938.47LO^2 - 1.185LALO + 1.1885LO^2LA^2 + 0.01494LA^2LO^3 \qquad (2)$$

Where:

R is the rainfall erosivity (MJ mm ha^{-1} h^{-1} $year^{-1}$);

Z is the altitude (m), LA is the latitude (decimal degrees), and

LO is the longitude (decimal degrees).

Subsequently, these values were classified according to Carvalho (2008): R < 2,452: low; 2,452 < R < 4,905: medium; 4,905 < R < 7,357: medium-strong; 7,357 < R < 9,810: strong and R > 9,810: very strong.

Soil erodibility (K)

When data collected in the field are available, the Bouyoucos equation (Equation 3) has been used (Anache et al., 2015; Khan et al., 2019). Thus, for each soil sample collected in the SRW (Figure 2), the K value was obtained based on sand, silt, and clay fractions. Subsequently, these K values were spatialized for the watershed using ordinary kriging, using the automap tool (Hiemstra et al., 2009), of the statistical software R.

$$K = \frac{(\%\ \text{sand} + \%\ \text{silt})}{\%\ \text{clay}}\ 0.01 \quad (3)$$

Where:

K is soil erodibility (Mg h MJ^{-1} mm^{-1}), and

% sand, % silt, and % clay represent the percentages of the sand, silt, and clay fractions, respectively, in the soil sample.

Typical erodibility values for the watershed soils were obtained from the literature. All values were obtained from field experiments conducted on soils in Rio Grande do Sul. The values used for erodibility factors were as follows: Yellow Argisol, 0.0300 (Denardin, 1990); Red-Yellow Argisol, 0.0338 (Silva, 2016); and Haplic Planosol, 0.0553 (Miguel, 2010).

Topographic factor (LS)

Among the numerous proposals for calculating the LS factor available in the literature, the methodology proposed by Moore & Burch (1986) (Equation 4) stands out. The authors proposed determining the LS factor by incorporating the unit potential energy, assuming that the water on the soil surface has energy capable of breaking down and transporting particles in the direction of the slope. In this way, it is possible to spatially represent the LS factor in areas of complex slopes, such as watersheds (Minella et al., 2010).

$$LS = \left[\left(\frac{FA_i b}{22.13}\right)^{0.40} \left(\frac{\text{sen}(\beta)}{0.0896}\right)^{1.3}\right] \quad (4)$$

Where:

FA is the accumulated flow (cell);

b is the spatial resolution of the cell (m);

β is the slope (degrees), and

i is a cell in the watershed matrix file.

Cover management and support practice factors (CP)

Values were obtained from the literature for the use and management of this study. All values were obtained from field experiments carried out on soils in São Paulo (grassland and annual cropping, soybean) and Rio Grande do Sul States (native forest), and RUSLE guide (water body and exposed soil). The values used for the cover factor were as follows: annual cropping, 0.2116 (Silva & Luchiari, 2016); water body, 0.00 (Wischmeier & Smith, 1978); exposed soil, 1.00 (Wischmeier & Smith, 1978); Grassland, 0.0500 (Silva et al., 2010); and native forest, 0.0150 (Silva et al., 2016). For the P factor, the value of 1.0 was used since no conservationist erosion control practices were identified, following the recommendations of Beskow et al. (2009) and Batista et al. (2017).

Tolerance of soil losses

The tolerance of soil loss (Table 2) was obtained using the methodology of Smith & Stamey (1964) (Equation 5).

$$T = 10\ (h\ Ds\ f) \quad (5)$$

Where:

T is soil loss tolerance (Mg ha^{-1} $year^{-1}$);

h is the effective soil depth limited to 1000 mm of each soil (mm);

f is a conversion factor related to the textural gradient, and

Ds is the soil density value (Mg m^{-3}).

TABLE 2. Tolerance of soil loss values for soils of Santa Rita Watershed (SRW), located in Southern Brazil.

Soil	f	h (m)	Ds (Mg m^{-3})	Tolerance (Mg ha^{-1} $year^{-1}$)
Yellow Argisol	0.4	1.00	1.52	6.06
Red-Yellow Argisol	0.6	1.00	1.52	9.10
Haplic Planosol	1.0	0.72	1.66	11.99

The effective soil depth (h) and density (Ds) were affected by the average values of the soil samples for each class. The conversion factor f converts the previously obtained soil loss tolerance into permanent soil loss. It was determined based on the textual gradient of the soil profiles, following the values proposed by Mannigel et al. (2002).

Classification index of soil loss

The index of soil loss (I_{SL}) allows the identification of regions in critical situations of soil loss (Ghafari et al., 2017; Sudhishri et al., 2014) and aims to create strategies for soil management and conservation. The I_{SL} was calculated using [eq. (6)] and was classified as follows: I_{SL} < 1, very low; 1 < I_{SL} < 2, low; 2 < I_{SL} < 4, medium; 4 < I_{SL} < 6, high; and I_{SL} > 6, very high.

$$I_{SL} = \frac{A}{T} \quad (6)$$

Where:

A is the soil loss measured by RUSLE (Mg ha^{-1} $year^{-1}$), and

T is the soil loss tolerance (Mg ha^{-1} $year^{-1}$).

RESULTS AND DISCUSSION

The erosivity values obtained for the SRW region (Figure 3a) showed that these range from 7,736.75 to 8,080.75 MJ mm ha^{-1} h^{-1} $year^{-1}$, with an average of 7,859.77 MJ mm ha^{-1} h^{-1} $year^{-1}$. According to Carvalho (2008), erosivity values in the SRW are classified as strong. The values obtained corroborate with the analysis carried out by Steinmetz et al. (2018) for the Pelotas and Fragata rivers watersheds, located in the Pelotas region, with erosivity values between 7,640.64 and 8,750 MJ mm ha^{-1} h^{-1} $year^{-1}$.

The values of factor R vary according to the DEM in the watershed; that is, the highest and lowest R values occur in places of higher and lower altitudes, respectively. Also noteworthy is the occurrence of higher R values in regions with Yellow Argisol (Figure 2a, Figure 3a).

The erodibility factor, through kriging, ranged from 0.03347 to 0.03512 (Figure 3b), with an average of 0.03464 Mg h MJ^{-1} mm^{-1}. In an experiment implemented by Denardin (1990), in Rio Grande do Sul, K values equal to 0.024, 0.032, and 0.034 Mg h MJ^{-1} mm^{-1} were observed for argisols, with an average of 0.030 Mg h MJ^{-1} mm^{-1}. Therefore, the estimated values for the same soil classes did not present great differences between those estimated in the present study. The most substantial differences for the K factor are observed in Haplic Planosol, for which the tabulated value is equal to 0.0553 Mg h MJ^{-1} mm^{-1}, whereas the average kriging is 0.0336 Mg h MJ^{-1} mm^{-1}. Kriging is a method that tends to soften the minimum and maximum values. As the area represented by Planosol is 2.17%, the interpolated values of K may have been affected by the smoothing effects imposed by the kriging method. The differences observed for the K-factor also indicate pedogenic variations resulting from the different climates of the region.

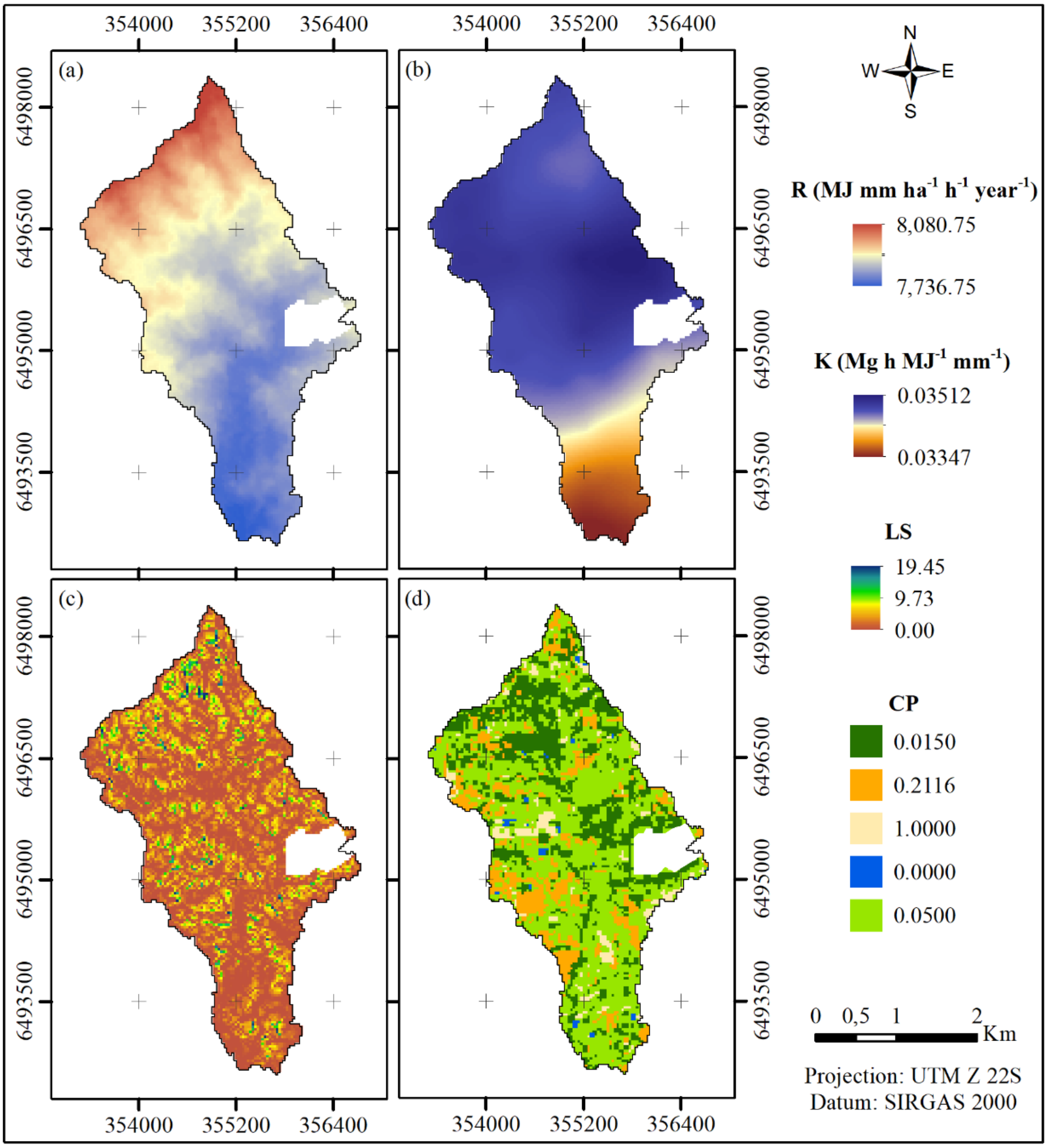

FIGURE 3. Rainfall erosivity (R), Soil erodibility (K), Topographic (LS), and Cover management and support practice (CP) factors for the Santa Rita Watershed (SRW), located in Southern Brazil.

The LS factor in the SRW ranges from 0 to 19.45 (Figure 3c), with an average of 1.35. According to Beskow et al. (2009), areas with LS < 10 can be considered to have low susceptibility to erosion. On analyzing the spatial distribution of the LS factor, areas with LS <10 represented 99.61% of the SRW, whereas higher values of the topographic factor were not very representative (0.65%). Furthermore, the LS values obtained for the SRW were higher in places with a greater slope and lower in flatter areas. The results of this study corroborate those obtained by Steinmetz et al. (2018) for two watersheds in the same region (LS = 0–25).

From Figure 3d, it can be seen that the predominant land uses in SRW are grassland and native forest located predominantly in flatter areas. The uses corroborate those found by Valadão et al. (2018) in the Fragata River watershed. However, no sites with exposed soil were identified, possibly due to the different stages of annual cropping development during the period in which the classification of both works was carried out.

Soil losses in the SRW range from 0 to 3,281.57 Mg ha^{-1} year^{-1} (Figure 4a), with an average annual loss of 35.94 Mg ha^{-1} year^{-1}. The greatest loss observed resulted from the combination of Yellow Argisol with exposed soil on strongly undulated slopes (Figure 5). In addition, it is possible to identify that both the higher portions of the watershed and the places with a predominance of exposed soil and annual cropping present the highest soil losses.

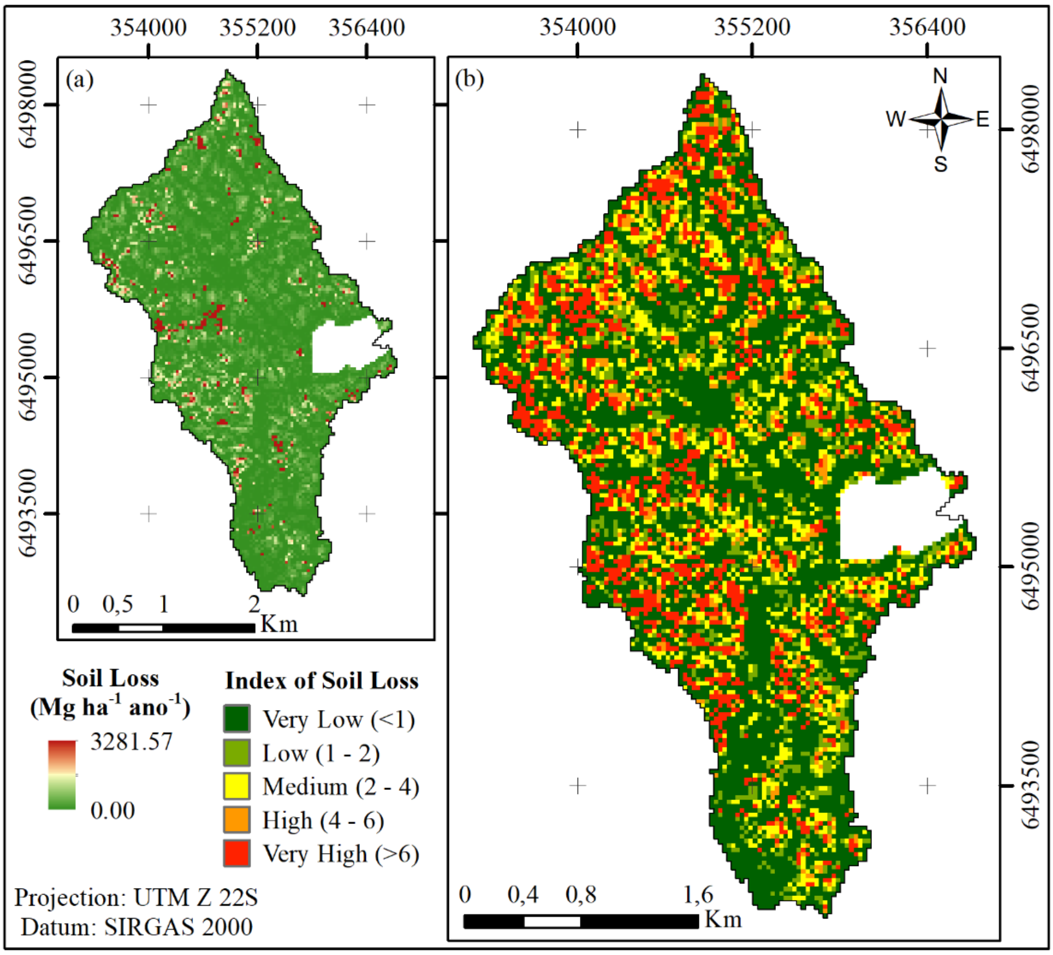

FIGURE 4. Soil Loss (a) and Index of Soil Loss (b) for the Santa Rita Watershed (SRW), located in Southern Brazil.

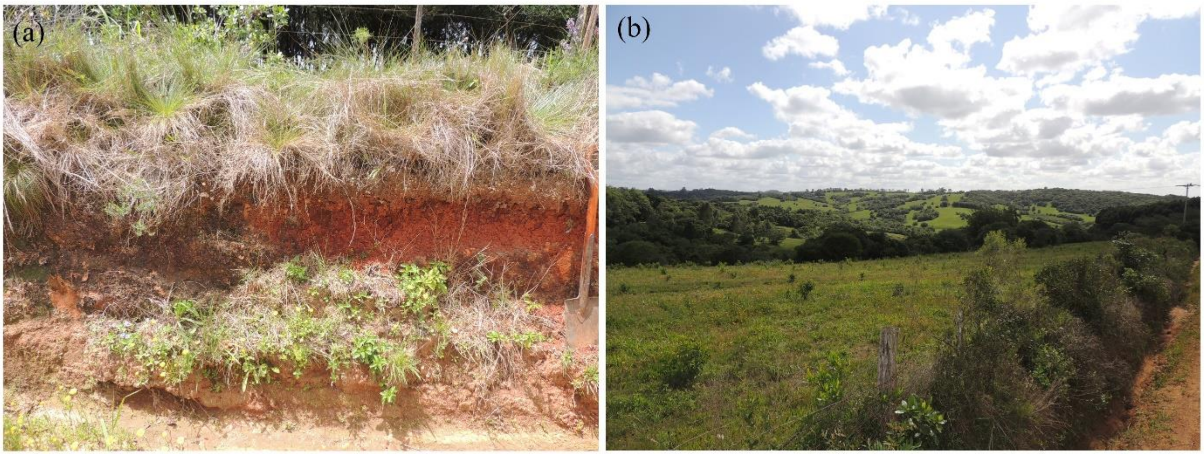

FIGURE 5. Yellow Argisol (a) and strong-undulated slopes (b) in the watershed Santa Rita (SRW).

Although SRW is a small watershed and has classes of land use that promote soil protection (grassland and native forest), it has critical areas susceptible to soil loss. This fact can be conditioned as much as the location of these areas in the landscape of the slope as to the intensity of the local rainfall. Thus, these findings are relevant to the planning and management of the watershed, subsequently enabling the adoption of techniques to control and prevent soil loss.

When only arbitrary classifications are considered for the soil loss process, there is a subjective understanding of the actual existence of areas with susceptibility to erosion in watersheds. Thus, the I_{SL} (Table 3) considers the rate of losses that are above tolerance, without the need to adopt arbitrary classifications because they vary with local geomorphology (Ghafari et al., 2017).

TABLE 3. Percentage of area associated with the classes established for the index of soil loss according to the class of soil, land use, and slope of the Santa Rita watershed (SRW), located in Southern Brazil.

Index Soil Loss Class		Very Low	Low	Medium	High	Very High
Classes analyzed		Area of SRW (%)				
Soil Class	Yellow Argisol	11.22	2.97	3.79	1.89	5.65
	Red-Yellow Argisol	40.19	8.02	10.55	4.40	9.15
	Haplic Planosol	1.87	0.22	0.06	0.00	0.02
Land Use Class	Native Forest	17.38	5.08	2.96	0.44	0.23
	Annual Cropping	6.01	0.22	0.53	0.61	6.74
	Exposed Soil	2.31	0.00	0.01	0.05	2.39
	Water Body	0.77	0.00	0.00	0.00	0.00
	Grassland	26.81	5.91	10.91	5.18	5.46
Slope Class	0% - 3%	10.12	0.68	0.29	0.10	0.23
	3% - 8%	24.90	5.29	3.95	1.40	3.44
	8% - 20%	17.86	5.12	9.64	4.56	10.24
	20% - 45%	0.39	0.11	0.53	0.23	0.92

A high incidence of very high values for the loss index (I_{SL} > 6) was observed in the Red-Yellow Argisol soil class (Table 3). These areas present the highest percentages of annual cropping and exposed soil as well as slopes of 8%–20%, which favors susceptibility to soil loss in SRW. At the same time, Red-Yellow Argisol also has a high incidence of very low values for the loss index (I_{SL} < 1) concentrated in places with grassland and native forest. Low I_{SL} values were observed in Planosols due to their location in the flatter portions of the slope and the good coverage and predominance of grassland (Figure 2). In addition, Haplic Planosol had the highest tolerance values (11.98) compared to Yellow Argisol (6.06) and Red-Yellow Argisol (9.10), which favored lower I_{SL} values (Figure 4).

In the Rio Grande watershed (Minas Gerais), Batista et al. (2017) observed a higher incidence of extreme loss classification values for annual crops and areas of exposed soil. In the SRW, it was noticed that the very high values of losses (I_{SL} > 6) are concentrated in annual crops and grassland areas. According to Wang et al. (2017), some grasslands may present a certain degree of degradation, which reduces vegetative cover and, consequently, soil protection. However, it is perceived that the high I_{SL} values observed in grassland areas are associated with higher values for other factors, mainly LS and R, emphasizing the need to implement integrated crop and grassland areas.

In areas with a slope lower than 8%, the lowest erosion rates predominate, whereas, in areas with more accentuated slopes, the highest percentages of medium to very high losses were found. The lower I_{SL} results from low LS values with a high percentage of areas with native forest, which provides adequate soil coverage (Didoné et al., 2015).

Although some characteristics indicate soil loss (e.g., exposed soil, high slope), an analysis is necessary considering all factors for decision-making. The continuous estimation of the K factor is predominant, allowing the spatialization of information and, consequently, the susceptibility to soil loss. Furthermore, the approach taken indicates soil management and conservation practices in the watershed, enabling the identification of the places where these practices should be applied.

CONCLUSIONS

Through variations in the classification of land use and erosivity in the Santa Rita watershed (SRW), which is located in southern Brazil, changes in the final estimates of losses are evidenced by the RUSLE model. It is recommended that agro-environmental management and conservation programs be directed to the areas with the greatest losses, especially those that vary between exposed soil and cultivated area during the year.

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